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Review of solar assisted heat pump drying systems for agricultural and marine products

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A B S T R A C T

Combining solar energy and heat pump technology is a very attractive concept. It is able to eliminate some difficulties and disadvantages of using solar dryer systems or solely using heat pump drying separately. Solar assisted heat pump drying systems have been studied and applied since the last decades in order to increase the quality of products where low temperature and well-controlled drying conditions are needed. This paper reviewed studies on the advances in solar heat pump drying systems. Results and observation from the studies of solar assisted heat pump dryer systems indicated that for heat sensitive materials; improved quality control, reduced energy consumption, high coefficient of performance and high thermal efficiency of the dryer were achieved. The way forward and future directions in R&D in this field are further research regarding theoretical and experimental analysis as well as for the replacement of conventional solar dryer or heat pump dryer with solar assisted heat pump drying systems and solar assisted chemical and ground source heat pump dryers which should present energy efficient applications of the technologies.

Contents

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1. Introduction

Utilization of the heat pumps for drying is interesting and very practical. Heat pump dryers possess high coefficient of performance and potential improvements in the quality of dried products due to heat pump's ability to operate at lower temperatures are major advantages of them and compatible with low-temperature drying operations. For the development of heat pump dryer, heat pump technology was used to enhance the economy and efficiency of conventional hot air dryer. Heat pump dehumidifiers in drying equipment are received much more attention due to their ability to recover the latent heat and transfer it to drying air which enable drying at lower temperatures, lower cost and operation even under humid ambient conditions and cause minimum environmental pollution [1]. It is worth remembering that if the dryer is working efficiently, the outlet air should have a temperature close to the wet bulb temperature and also be at high humidity. Therefore, the majority of the gas enthalpy is the latent heat in moisture vapour and heat recovery should, when possible, include moisture condensation from the drying air. This method is applied in heat pump dehumidifiers [2].

The three major advantages of heat pump dryers are [3]:

1. Drying at low temperatures can improve quality.
2. Higher energy efficiencies are achieved because both the sensible and the latent heat of evaporation are required.
3. Drying conditions and therefore drying rate is unaffected by drying conditions.

The principle of the heat pump, which is the same as that involved in the refrigeration operation cycle, has been known for over 100 years. In the last three decades, heat pump applications have been limited only by economics [2]. It is worth noting that against these advantages, the use of electrical energy which is generally more expensive than other forms of energy and the advent of the energy crisis in the early 1970s led to several concerns related to finding alternative energy resources for electricity in industrial application, therefore, the application of heat pump drying was limited.

The traditional refrigeration cycles are driven by electricity or heat, which strongly increases the consumption of electricity and fossil energy. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the whole world is employed for refrigeration and air-conditioning processes of various kinds, and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings. Moreover, peak electricity demand during summer is being re-enforced by the propagation of air conditioning appliances [4–6].

In order that optimize product quality of specialty crops such as herbs, ginseng, etc., there is a need to dry them at low temperatures (30–45 °C) and relative humidity. This is an important consideration as these herbs have relatively high commercial as well as medicinal values. High temperature drying deteriorates the material structure and can render it unsuitable for further use [7]. Low temperature drying of specialty crops reduces the risk of loss in nutrient content and damage to physical properties. Drying system incorporating a heat pump where both sensible and latent heats are recovered from the exhaust air. The heat is then recycled back through the dryer by heating the air entering the dryer [8]. Relatively few heat pumps are currently installed in industry. However, as environmental regulations become stricter, industrial heat pumps can become an important technology to reduce emissions, improve efficiency [9], and limit the use of ground water for cooling. Heat pumps are used extensively in industrial dehumidification and drying processes at low and moderate temperatures (maximum 100 °C). The main applications are drying of pulp and paper, various food products, wood and lumber. Because the drying is executed in a closed system, odours from the drying of food products, etc. are reduced [10].

So as to benefit from the free and renewable energy source provided by the sun numerous attempts have been made in recent years to develop solar drying systems mainly for preserving agricultural and forest Products [11]. Solar drying technology offers an alternative which can process the products in clean, hygienic and sanitary conditions [12] with zero costs, abundance in nature, cheap, renewable, low environmental impact and represents a good source of thermal energy, but has some disadvantages. First, the intensity of incident radiation is a function of time. This is a circumstance and demands adequate control strategy and the means necessary for such control. Another problem is caused by the low energy density of solar radiation which requires use of large energy-collecting surfaces [13]. Thirdly, it may be necessary to match the drying kinetics of the product to that of the time-varying solar radiation density else thermal-related product quality parameters such as texture and colour can undergo significant degradation. Therefore, it is imperative that, a more scientific method for drying has emerged termed as controlled solar drying [12].

Combined solar dryer and heat pump can overcome these difficulties and satisfy important demands in industrial drying with respect to product quality control, reduced energy consumption and reduced environmental impact. For heat sensitive materials improved quality control can be achieved due to low drying temperatures and independency of the outdoor air. Reduced energy consumption is achieved due to the high coefficient of performance of the heat pump and the high thermal efficiency of the dryer when properly designed [14].

This paper presents the advances in solar assisted heat pump drying system and the research and development directions in the field.

2. Heat pump

Heat pumps are coolers (refrigerators) that raise the energy gained by cooling from a low-temperature energy carrier with the aid of further external (driving) energy to a higher temperature level and transfers it from there to an energy-carrying medium [15–17]. The term heat pump refers to the fact that both the cooling and the heating performance of the refrigerator are utilized [17].

2.1. The basic of heat pump

In the heat pump, cooling and dehumidification of the air is provided in the evaporator as low temperature refrigerant entering the evaporator as a mixture of liquid and vapour is vaporized by thermal input from the load (Fig. 1). The refrigerant vapour enters the suction line of the compressor in a saturated or slightly superheated condition that raises the pressure and, consequently, the temperature of the refrigerant. The high pressure and temperature refrigerant vapour enters a condenser heat exchanger that uses ambient air or water to cool the refrigerant to its saturation temperature prior to fully condensing to a liquid condition after condenser [18]. At the condenser, the refrigerant undergoes two-phase condensation, changing from vapour to liquid phase. During this process, heat is rejected by the condenser to heat the surrounding air or water. A throttling device such as a valve, orifice plate, or capillary tube is used to expand the liquid refrigerant which causes some of the refrigerant to vaporize as its temperature and pressure is reduced. After the expansion process, the refrigerant enters the evaporator in a two-phase state. The cycle repeats again [19].

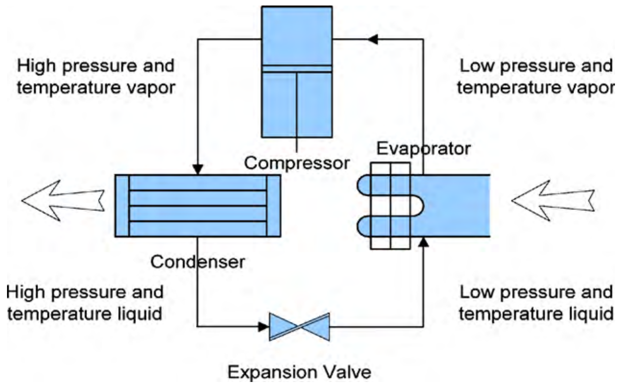


Fig. 1. Schematic diagram of basic air-to-air heat pump cycle

2.2. Refrigerants

Refrigerants are the working fluids in mechanical vapour compression cycle. For the past few decades, CFCs and hydro chlorofluorocarbons (HCFCs) have been extensively used in refrigeration, heat pump dryer and air-conditioning fields due to their excellent thermodynamic and chemical characteristics [20]. Molina and Rowland [21] in 1974, suggested that CFCs might be responsible for the destruction of the stratospheric ozone layer and since then much efforts were expended to examine if their suggestion was correct. Consequently in 1987 [22], many nations signed the Montreal Protocol to regulate the production and trade of ozone depleting substances, realizing that ozone layer-depletion is a global environmental issue. As a result of this international agreement, CFCs are completely phased out as of January 1996 in the developed countries while they are allowed for further use for another 10 years in the developing countries. In order to fill the gap caused by the phase-out of CFCs, refrigeration, air-conditioning industry and the food industry has carried out extensive research and development activities to find alternative pure refrigerants. There are a large number of alternative refrigerants on the market. Table 1 lists some of these alternatives [23]. In ASHRAE Standard 34 [24], refrigerants are classified according to the hazard involved in their use. The toxicity and flammability classifications yield six safety groups (A1, A2, A3, B1, B2, and B3) for refrigerants. Group A1 refrigerants are the least hazardous, Group B3 the most hazardous.

2.3. Heat pump applications

There are few heating and cooling applications that cannot benefit from heat pump technology and in doing so deliver significant energy efficiencies.

Heat pumps are available to claim free or waste heat from a number of places such as: ambient air, ground water, the ground itself, commercial applications where unwanted heat would be rejected.

Heat pump technology can be used in domestic and commercial applications as diverse as space heating or cooling for human comfort in offices, homes, water heating and all kinds of residential installations. They can also be found in commercial applications where large quantities of air are available for drying, swimming pools and factory production [25].

3. Heat pump drying

There are various ways of drying moist materials and it is often necessary to compare the efficiencies of different methods. A convenient parameter to use is 'effectiveness' which refers to the amount of water extracted per unit energy input, expressed in kg H_2O kW h^{-1} [26]. The simplest drying method is to blow heated air over the moist material and to vent the moist air to atmosphere [27,28]. An improvement is possible by recalculating a proportion of the air but the amount of improvement is limited and it is at the expense of increased drying time.

One of the most efficient and controllable ways of drying moist materials is by using a heat pump drying. For years heat pumps have been known as an efficient method of energy recovery. Heat pump for drying is difference of the hot heat produced by condenser and cold heat by the evaporator will be use concurrently during the operation. The heat from the condenser will produced hot and will use to heat the material and the cold heat from the evaporator will be use in dehumanization process (Fig. 2).

The application of heat pump in agriculture started out with their use as supplementary devices for heating. Subsequent research and development has resulted in developing of drying process that run solely with a heat pump. The commercial use of heat pump assisted dryer has been reported in many parts of Europe, Asia and Australia where technology has been applied mostly in the marine food-processing sector [29].

3.1. Classification of heat pump dryer

The most common heat sources for drying applications are air, ground and chemical source heat pumps. Amongst them, air source heat-pumps have been widely used in drying applications. Classification scheme for heat pump dryers is given in Fig. 3.

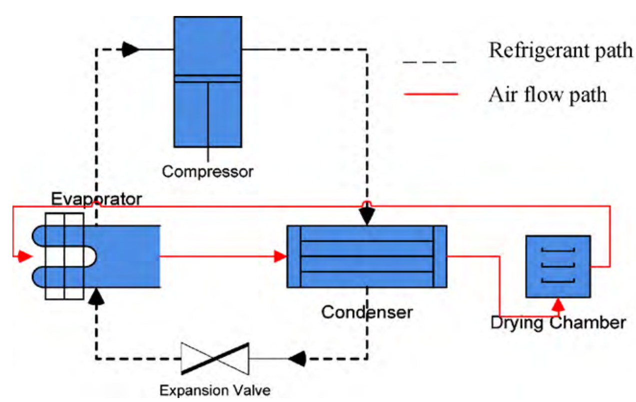


Fig. 2. Schematic diagram of a heat pump dryer

Table 1
Some alternative refrigerants.

Refrigerants	Chemical formula/composition (mass%)	Molecular weight	Critical temperature (°C)	Critical pressure (bar)	Safety
R134a	CH_2FCF_3	102	101.1	40.7	A1
R409a	R-22/124/142b (60.0/25.0/15.0)	97.5	107	46	A1
R22	$CHClF_2$	86.48	96.1	49.9	A1
R404A	R-125/143a/134a (44.0/52.0/4.0)	97.6	72.4	36.9	A1
R507	R-125/143a (50.0/50.0)	98.9	76.1	37.9	A1
R717	NH_3	17.03	132.4	111.5	B2
R290	$CH_3CH_2CH_3$	44.10	96.8	42.4	A3

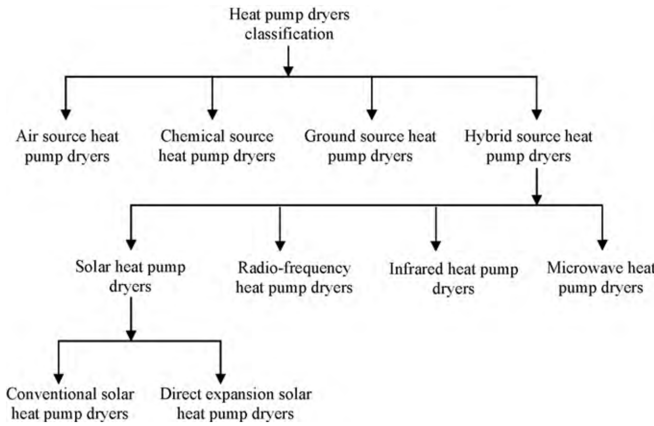


Fig. 3. A classification of heat pump dryers

3.2. A review on heat pump-assisted dryer

The ability of heat pumps to convert the latent heat of vapour condensation into the sensible heat of an air stream passing through the condenser makes them attractive in drying applications especially when combined with the capability to produced well-controlled drying conditions [30]. For these reasons heat-pump drying has been used for decades in wood kilns to dehumidify air and lumber quality [31].

3.2.1. Air source heat pump drying systems

Following the general trend to improve product quality and reduce energy consumption, many researcher have acknowledged the specific features of heat pumps, which has resulted in the rapid growth of both theoretical and applied research on air source heat pump drying (Table 2).

The key advantages and limitations of heat pump dryers are as follows [66]:

Advantages:

- Higher energy efficiency with controlled temperature profile to meet product requirements.
- Better product quality with control temperature profile to meet product requirements.
- A wide range of drying conditions typically from −20 to 100 °C (with auxiliary heating) is feasible.
- Consistent output of products.
- Excellent control of the environment for high value products and reduced electrical consumption for low-valued products.
- Suitable for both high-value and low-value products.
- Aseptic processing is possible.
- Another feature of the heat pump dryer is its characteristic low energy consumption [67,68].
- Preliminary studies found that the colour and aroma qualities of dried agricultural products using heat pumps were better than those products using conventional hot air dryers [38,41,43,53].

Limitations:

- Auxiliary heating may be required for high-temperature drying due to the critical pressure level of some refrigerants.

Table 2
Selected studies in air source heat-pump drying (agricultural and marine products).

Source	Location	Application(s)	Remarks
Theerakulpisut [32]	Australia	Grain	An open cycle HPD performed better during the initial stage when the product drying rate is high.
Meyer and Greyvenstein [33]	South Africa	Grains	The HPD is more economical than other dryers.
Rossi et al. [34]	Brazil	Vegetable (Onion)	Better product quality and energy saving of the order of 30% was obtained.
Mason and Blarcom [35]	Australia	Macadamia nuts	The advantages of dehumidified heat pump drying on drying rate investigated.
Strommen and Kramer [36]	Norway	Marine products (fish)	The high quality of the dried products was Highlighted as the major advantage of HPD.
Vazquez et al. [37]	Spain	Grape	The drying kinetics of grape to modify the structure and composition of the grape skin and, thereby, to reduce the drying time and improve the quality of the final product described.
Prasertsan and Saen-saby [38,39]	Thailand	Agricultural food drying (bananas)	HPD is economically feasible and for drying high moisture materials is so appropriate.
O'Neill et al. [40]	New Zealand	Apples	Modified atmosphere heat pump system drying (MAHPD) produces products with a high level of open pore structure, contributing to the unique physical properties.
Soponronnarit et al. [41]	Thailand	Papaya glace	SMER was 0.363 kg water evaporation/kWh at specific air flow rate of 21.42 kg dry air/h-kg. COP was varied between 3.71 and 3.85. The colour was light reddish-orange.
Fatouh et al. [42]	Egypt	Onion, carrot, potato and sweet potato	In continues drying specific energy consumption lower than the conventional dryers by 18–32% are achieved.
		Onion	The intermittent and continuous drying technique showed that the use of intermittent drying saves about 30% of the energy consumed by the continuous drying when the appropriate heating and resting periods are used.
Strommen et al. [43]	Norway	–	HPD with hydrocarbon and natural working fluids can save significant amounts of energy. With comparison the performance of several refrigerants, they found that ammonia was the most favourable refrigerant in the temperatures: 30–80 °C.
Chou et al. [44–46]	Singapore	Mushrooms, fruits, sea cucumber and oysters	Author suggested with scheduled drying conditions the quality of products can be improved.
Jon et al. [47]	Singapore	Potato	Overall colour change in potato was minimum, when subjected to a higher varying dry temperature.
Achariyaviriya et al. [48]	Thailand	Papaya glace	Results showed that ambient conditions affected significantly on the performance of the open loop dryer and the partially closed loop dryer. Also, the fraction of evaporator bypass air found that specific air flow rate and drying air temperature affected significantly the performance of all heat pump dryers.

Table 2 (*Continued*)

Source	Location	Application(s)	Remarks
Ho et al. [49]	Singapore	Potato slice	A material model and heat transfer in a potato slice as a model for heat-sensitive product was formulated and validated.
Chua et al. [50]	Singapore	Banana	A two-stage heat pump dryer capable of producing stepwise control of the inlet drying air temperature while keeping absolute humidity constant used. By employing stepwise-varying drying air temperature, it was possible to reduce significantly the drying time with improved product colour.
Adapa et al. [7]	Canada	Crops	A simplified procedure for modelling the performance of a low temperature heat pump dryer was developed.
Teeboonma et al. [51]	Thailand	Fruits (papaya and mango glace)	Mathematical models of fruits drying using HPD were developed and validated experimentally. The optimum criterion is minimum annual total cost per unit of evaporating-water. The effects of initial moisture content, cubic size and effective diffusion coefficient of products on the optimum conditions of HPD are also investigated. exergy and energy analysis was made.
Dandamrongrak et al. [52]	Thailand	Banana	The effects of blanching, chilling, freezing, and combined blanching and freezing investigated in a heat pump dehumidifier dryer. blanched sample was most preferred in terms of colour while the frozen samples exhibited extensive browning. The texture and flavour was significantly ($P<0.05$) reduced in all samples that involved blanching and/or freezing.
Kohayakawa et al. [53]	Brazil	Mango	The energy efficiency improved compared with electrical resistances dryer.
Queiroz et al. [54]	Brazil	Tomato	Heat pump effective coefficient of performance (COPHT,EF) was between 2.56 and 2.68, with an energy economy of about 40% when compared to the drying system with electric resistance.
Zhang et al. [55]	China	Carrots cubes	A heat pump in combination with fluidized bed dryer was designed and studied. The moisture extraction rates (MER) and the specific moisture extraction rates (SMER) of carrots drying decreased rapidly with time. The maximum average MER, SMERhp and SMERws was 3.63 kg/h, 1.25 kg/kWh and 0.715 kg/kWh, respectively. The energy consumption of compressor is approximate 50% of the total energy input.
Fatouh et al. [56]	Egypt	Jew's mallow, spearmint and parsley	Drying characteristics are influenced by surface load, drying air temperature and drying air velocity. The surface load and drying air temperature have larger effects than that of the drying air velocity on both the dryer productivity and the specific energy consumption.
Hawlader et al. [57]	Singapore	Sliced West Indian ginger	A heat pump dryer using normal air, nitrogen, and carbon dioxide was selected and inert gas heat pump drying showed an improved effective diffusivity and a better retention of flavor.
Hawlader et al. [58]	Singapore	Apple, guava and potato	Modified atmosphere heat pump dryer produced better physical properties.
Chegini et al. [59]	Iran	Plum	The optimum temperature of drying for plums is in vicinity of 70–80 °C; also (SMER) of designed dryer was notably more than conventional types of dryers in respect to saving the energy.
Ceylan and Aktas [60]	Turkey	Hazelnut	Heating coefficient of performance of whole system (COPws) of the heat pump dryer was calculated as 1.70 for 50 °C, 1.58 for 45 °C and 1.40 for 40 °C drying air temperatures. Energy utilization ratio changed between 24% and 65% for 50 °C, 17 and 63% for 45 °C and 14 and 43% for 40 °C drying air temperatures in the heat pump dryer.
Sunthonvit et al. [61]	Australia	Fruit – Nectarines	A heat pump dryer was the best system for preservation of volatile compounds in sliced dried fruit in terms of lactones and terpenoids followed by cabinet dryer and tunnel dryer.
Coogan and Wills [62]	Australia	Asian white radish pieces	The level of the primary flavor compound, 4-methylthio-3-trans-butenyl isothiocyanate (MTBITC), decreased in all treatments: using a hot air drier, a heat pump drier and a freeze drier, and whole roots were partially dried by salting under pressure with sodium chloride. Radish dried with hot air and heat pump driers showed increasing MTBITC loss with increasing drier temperature with a lower loss in the heat pump drier with the rate of drying also faster with the heat pump drier.
Phoungchandang [63]	Thailand	Garlic and White mulberry	The results revealed that drying air temperature and relative humidity influenced the drying curves and were included in the model. Computer simulation model of the heat pump dehumidified drying shown to be in good agreement with experimental results.
Aktaş et al. [64]	Turkey	Apples	A system which is composed of the combination of both dryers (Heat pump and solar dryer) is considered to be more efficient.
Daghigh et al. [65]	Malaysia	Agricultural and marine products	The results of performance and economic analysis of an air source heat pump assisted-drying system presented and the relations between these were showed in a nomogram which designed to allow the approximate graphical computation of a function and to predict the system performance graphically for wide ranges of evaporator and condenser temperatures and make a connection between them.

- Initial capital cost may be high due to many refrigerant components. Requires a steady state period for system to attain desired drying conditions.
- Required regular maintenance of components.
- Leakage of refrigerant to the environment if cracking of pipes occurs due to pressurized systems.

3.2.2. *Chemical heat pump drying systems*

Chemical heat pumps (CHPs) are thermal energy management systems that have several uses permitting a number of simultaneous functions and requiring no mechanical energy input. These uses include thermal energy storage, heat pumping, improving heat quality and refrigeration [69,70]. Among industrial processes,

certain unit operation such as drying, distillation, evaporation and condensation deal with large amount of enthalpy changes where CHP can be effectively utilized [71]. In recent years some studies have been conducted in using chemical heat pump drying systems.

A new chemical heat pump (CHP) system for ecofriendly effective utilization of thermal energy in drying is proposed from the viewpoints of energy saving and environmental impact. CHPs can store thermal energy in the form of chemical energy by an endothermic reaction and release it at various temperature levels for heat demands by exo/endothermic reactions. CHPs have potential for heat recovery and dehumidification in the drying process by heat storage and high/low temperature heat release. In this study, the authors estimate the potential of the CHP application to drying systems for industrial use. Some combined systems of CHPs and dryers are proposed as chemical heat pump dryers (CHPD). The potential for commercialization of CHPDs is discussed [72].

Results of an experimental study of a chemical heat pump (CHP) assisted convective dryer (Fig. 4) showed that it can be used for hot air production for batch drying using ambient air temperature in the heat-release step. The CHP unit can be operated to increase the temperature level and also to dehumidify the air, which is a particularly attractive feature for drying. Results are presented for a single cylindrical reactor to study the effects of the heat exchange conditions on hot air production. The results show that the hot air production is improved by enlarging the heat exchanger, increasing the heat transfer rates by use of stainless mesh and increasing the air flow rate [73].

The results of an experimental investigation on the controllability of hot air production using a pair of chemical heat pumps (CHP) presented. The objective of this study was to determine how a CHP-assisted batch dryer can be operated effectively. The CHP uses the well-known $CaO/H_2O/Ca(OH)_2$ hydration/dehydration reaction, which is reversible. The hot air temperature can be controlled by adjusting the reactor temperature, and pressure, as well as thermal power supplied to it. It was shown that hot air can be produced in both the heat storage and heat release steps of the CHP [74].

3.2.3. Ground source heat pump dryer

A ground-source heat pump (GSHP) transforms the earth energy into useful energy to heat and cool. It provides low-temperature heat by extracting it from the ground or a body of water. It can actually produce more energy than it uses, as it draws additional free energy from the ground [75]. There are various studies on the ground source heat pump (GSHP) systems [76–96], whereas, few studies have been conducted regarding utilization of this kind of heat pumps for drying applications.

A ground-source heat pump (GSHP) utilizes the ground as a heat source in heating and a heat sink in cooling mode operation. In the heating mode, a GSHP absorbs heat from the ground and uses it to heat working fluid. GSHPs are an efficient alternative to conventional methods of conditioning homes because they utilize the ground as an energy source or sink instead of using the ambient air. The ground is a thermally more stable heat exchange medium than air, essentially unlimited and always available. The GSHPs exchange heat with the ground, and maintain a high level of performance even in colder climates [97].

An exergetic assessment of a ground-source (or geothermal) HP (GSHP) drying system presented. This system was designed, constructed and tested in the Solar Energy Institute of Ege University, Izmir, Turkey. The exergy destructions in each of the components of the overall system are determined for average values of experimentally measured parameters. Exergy efficiencies of the system components are determined to assess their performances and to elucidate potentials for improvement. COP values for the GSHP unit and overall GSHP drying system are found to range between 1.63–2.88 and 1.45–2.65, respectively, while corresponding exergy efficiency values on a product/fuel basis are found to be 21.1 and 15.5% at a dead state temperature of 27 °C, respectively. Specific moisture extraction rate (SMER) on the system basis is obtained to be 0.122 kg kW^{-1} h^{-1}. For drying systems, the so-called specific moisture exergetic rate (SMExR), which is defined as the ratio of the moisture removed in kg to the exergy input in kW h, is also proposed by the authors. The SMExR of the whole GSHP drying system is found to be 5.11 kg kW^{-1} h^{-1}[98].

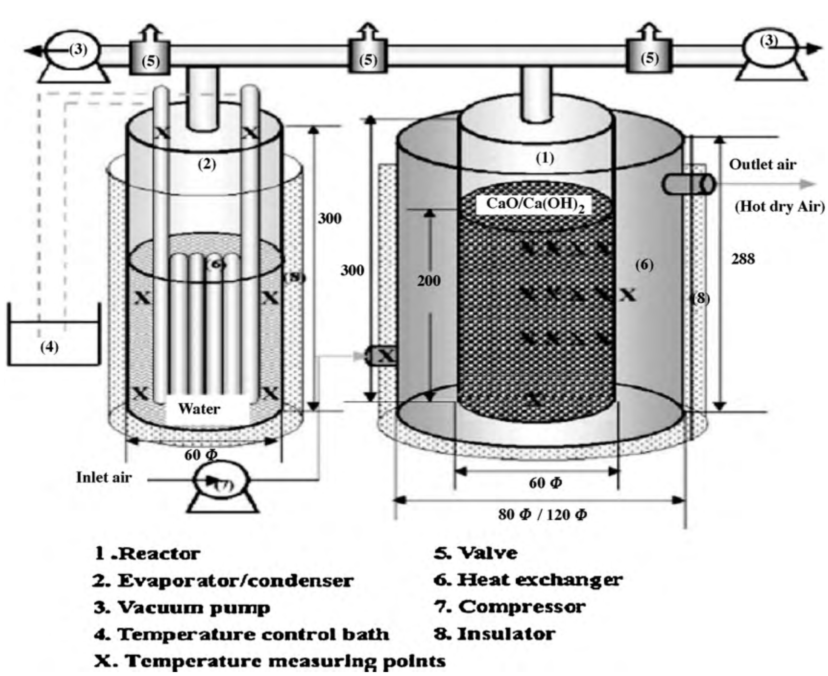


Fig. 4. Standard-type CHP unit [73]

The exergy analysis of a single layer drying process of mint leaves in a ground source heat pump tray dryer, which was designed and constructed in the Solar Energy Institute, Ege University, Izmir, Turkey presented. The drying process was realized at three various drying air temperatures of 40, 45 and 50 °C, and mass flow rate from 0.01 to 0.05 kg/s at a constant relative humidity of 16%. The effects of temperatures and mass flow rates on the exergy losses, exergy efficiencies and improvement potentials of the drying process were investigated. Maximum exergy efficiency of the drying chamber was obtained at a temperature of 50 °C and a drying air mass flow rate of 0.05 kg/s. The exergy efficiency values were obtained to vary from 76.03% to 97.24% at drying air temperatures of 40–50 °C with drying air mass flow rates of 0.01–0.05 kg s^{-1} [99].

The exergy analysis of the single layer drying process of laurel leaves in a ground-source heat pump drying cabinet, which was designed and constructed in the Solar Energy Institute, Ege University, Izmir, Turkey showed. The effects of drying air temperature on exergy losses, exergy efficiencies and exergetic improvement potential of the drying process were investigated. The results have indicated that exergy efficiencies of the dryer increase with rising the drying air temperature. Moreover, the laurel leaves are sufficiently dried at the temperatures ranging from 40 to 50 °C with relative humidities varying from 16 to 19% and a drying air velocity of 0.5 m s^{-1} during the drying period of 9 h. The exergy efficiency values are obtained to range from 81.35 to 87.48% based on the inflow, outflow and loss of exergy, and 9.11–15.48% based on the product/fuel basis between the same drying air temperatures with a drying air mass flow rate of 0.12 kg s^{-1}[100].

4. A systematic classification of solar assisted heat pump (SAHP)

A solar assisted heat pump system is composed of a vapour compression cycle unit which is combined with a solar collector and this combined system possesses a high coefficient of performance [101–103]. Solar assisted heat pump systems can be classified to conventional SAHP systems and direct-expansion SAHP (DX-SAHP) systems. In a direct system (Fig. 5), solar collector system does not act as evaporator and it is comprise of one heat pump (evaporator, condenser, compressor and expansion vale) and solar collector. The DX-SAHP system basically consists of a solar collector, a heat exchanger as condenser, a thermostatic expansion valve and a compressor. The solar collector is used as the evaporator of the heat pump system. The refrigerant is directly vaporized in the solar collector–evaporator due to the solar energy input, where phase change from liquid to vapour occurs. Thus, unlike the conventional SAHP systems, where two separate system components are used for the same purpose, both processes, namely collecting solar energy and vaporizing the refrigerant, are realized in one unit only [104]. This leads to several advantages compared to conventional SAHP systems [104]:

(a) The direct vaporization of the refrigerant in the solar collector–evaporator leads to higher heat transfer coefficients.
(b) The use of the solar collector as the evaporator reduces overall system cost because the need for an additional evaporator in the traditional SAHP system is eliminated.
(c) Problems, which may occur in water collectors (i.e. corrosion, night freezing), are eliminated due to the use of refrigerants as the working fluid, leading to longer system life.
(d) Using refrigerants as the working fluid in the heat pump cycle results with low temperature during the evaporation process in the solar collector, which leads to lower system losses since the collector loss value is a function of the collector to ambient temperature difference.
(e) The collector, including bare flat-plate collectors, works at high efficiency values based on the low collector to ambient temperature differences, which also reduces collector cost.

5. A brief description of solar assisted heat pump drying (SAHPD) technology

Heat pumps have been known to be energy efficient when used in conjunction with drying operation. The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust air as well as their ability to control their dryer air temperature and humidity [105].

There can be a variety of SAHPD designs depending on nature of the direct application such as one with and without heat storage facility. Fig. 6 illustrates the schematic of a simplified SAHPD system. It represents a schematic layout of the various refrigeration components and solar system integration with the drying chamber. The inlet drying air passes through the drying chamber and picks up moisture from the product [105]. The humid air from the dryer is passed over the evaporator of the heat pump which acts as dehumidifier [106]. During the dehumidification process, the humid air is first cooled sensibly to its dew point. Further cooling results in water being condensed from the air. Both sensible and latent heats are then absorbed by the evaporator for boiling of the refrigerant. The recovered heat is pumped to the condenser, where it is heated by the condensing working fluid. At the solar collector, the solar radiation from the sun is converted to sensible heat. Air passing through the number of pipes in the panel is then heated up. This heated air entering the condenser. The pre-heated and dehumidified air absorbs more heat from the condenser and then one that is higher temperature and properly

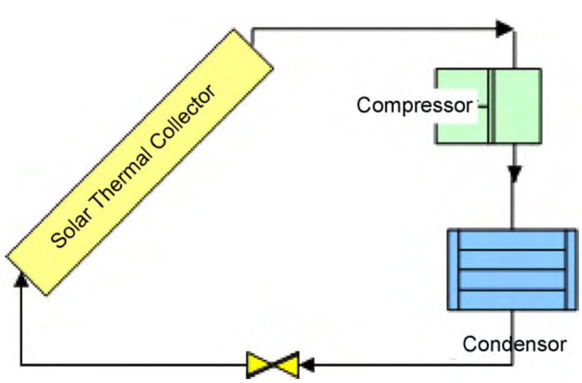


Fig. 5. Schematic diagram of a direct expansion solar heat pump

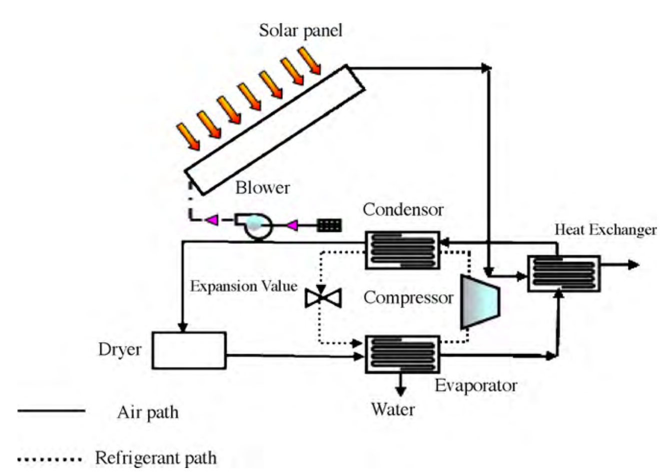


Fig. 6. Schematic of a simplified SAHPD system

dehumidified which readily flows through the drying chamber for drying application.

Like many mechanical systems, the SAHPD has a set of advantages and disadvantages. The potential advantages of SAHPD are [105]:

- Easy conversion of natural energy for direct heating and storage resulting in significant saving of energy and better system efficiencies.
- Better product quality with well-controlled drying condition schedules to meet specific production requirements.
- Easy to implement control strategy.
- Higher operating drying temperature compared to a standalone heat pump drying system.
- Because heat pumps consume less primary energy than conventional heating systems, they are an important technology for reducing gas emissions that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x). However, the overall environmental impact of electric heat pumps depends very much on how the electricity is produced. Heat pumps driven by electricity from, for instance, hydropower or renewable energy, reduce emissions more significantly than if the electricity is generated by coal, oil or gas-fired power plants [10].

Disadvantages are as follows [107]:

- Higher capital costs incurred for additional solar panels, blowers, storage tanks, etc.
- The amount of available solar energy varies significantly throughout the day.

5.1. Solar assisted heat pump drying systems

Unification of solar collectors and HPD in places where abundant solar energy sources are available may further increase the drying temperature and energy efficiency of the overall drying system. The collection of solar energy and setting aside for future use in a phase-change material such as paraffin wax for discharging sensible energy to the drying air leads to a cheaper means of employing higher drying temperature in comparison with conventional heating system. Further, such a system offers the flexibility of operating with the heat pump, solar system, or with both systems complementing each other. A solar collector-cum-rocked bed storage system for peanut drying has experimentally evaluated by Troger and Butler [107,108].

Chauhan et al. [107,109] studied the drying characteristics of coriander in a stationary 0.5 t/batch capacity deep-bed dryer coupled to a solar air heater and a rock bed storage unit to receive hot air during off sun shine hours. They found that to reduce the average moisture of coriander grains from 28.2 (dry basis) to 11.4% (dry basis) requires 27 cumulative sunshine hours. Using the store d heat from the rock bed energy storage system, the removal of the same moisture can be accomplished with just 18 cumulative sunshine hours. The solar energy supply system proposed in this section consists of solar collectors, blowers, phase change storage tank, air-valves, and pipes as shown in Fig. 6. Depending on the type of drying material which determines the air temperature, the air may be flown with open full partial discharge circulate on or full discharge circulation mode.

Fig. 7 shows the schematic arrangement of a solar dryer equipped with absorption heat pump and heat storage [110,111]. A part of the enthalpy of entering outside air1 is used—interposing pump system 2—for evaporating sprayed water in an evaporator 3. The water vapor goes over to the brine sprayed into tank 4. Pump 5

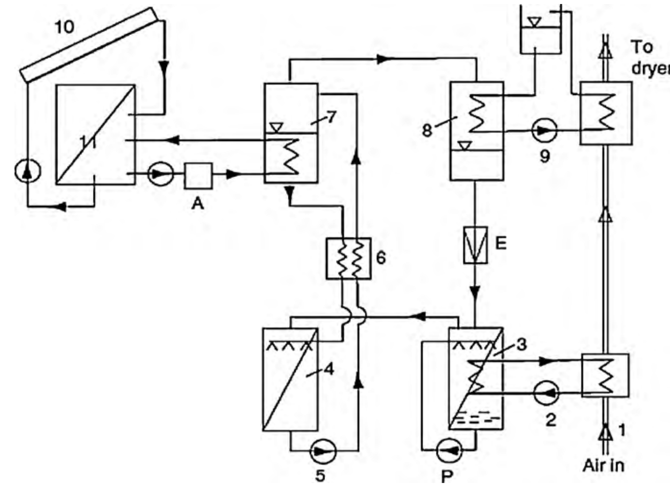


Fig. 7. Solar dryer for peanuts equipped with absorption heat pump and heat storage [111].

feeds the brine through a regenerator heat exchanger 6 into a high-pressure boiler 7. Water in the boiler is distilled with the help of solar energy obtained in a collector 10 and stored in a water tank 11, and by using auxiliary energy A to the extent necessary the strong solution is led back into tank 4 through regenerator 6. The high-pressure water vapor condenses in condenser 8 and with the help of the pump heat exchanger system 9 warms the air of reduced moisture content, which is supplied to the dryer. The condensed high-pressure water flowing through an expansion valve E cools and arrives in evaporator 3. This system was originally designed for drying peanuts.

Fig. 8 illustrates the scheme of a system complete with a heat pump [111,112]. Part of the moist air leaving the dryer flows through the evaporating heat exchanger 9 of the heat pump, and a proportional part of its moisture content is condensed. The heat input to the working medium of the heat pump (complemented by the input energy of compressor 10 and with the aid of the con denser heat exchanger 11) can be taken into the hot water system. Depending on the ambient state, the air leaving heat exchanger 9 can be returned to heat exchanger 6 of the dryer. In the case of a dryer connected to the energy system of cattle-raising farm, a heat pump can be also used for cooling milk and producing hot water at the same time.

The fluid medium collector system 5 built on top of the dryer building is connected to a closed circuit. The system can have

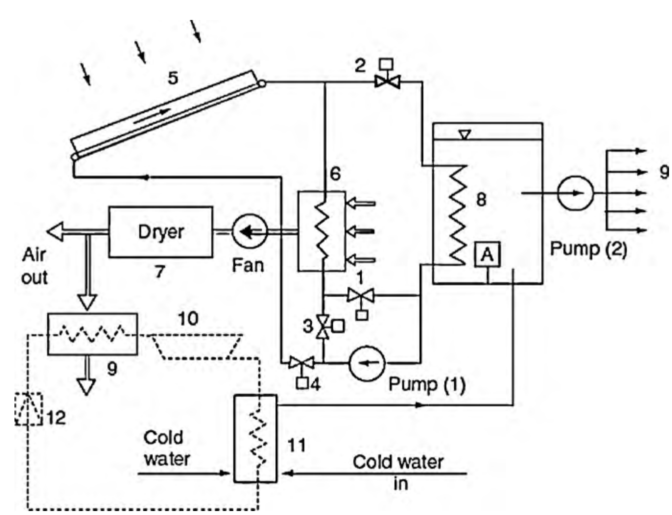


Fig. 8. Complex solar dryer systems combined with heat pump [111].

different operating mo des. When valves 2 and 3 are closed, the collector system works on the fluid–air heat exchanger 6 and serves dryer 7. With valves 1 and 3 closed, the water heat storage 8 is warmed. In the transition position of valves 1 and 2 (valve 3 is closed), the two mo des can partially operate simultaneously. If valves 1 and 4 are closed, the drying air is warmed in heat exchanger 6 by using the hot water reserves of heat storage 8.The air leaving the dryer has almost the same enthalpy it had on entering the dryer. A considerable part of the enthalpy used on drying can be regained by condensing the absorbed water vapour. For this purpose a heat pump may be inserted in the energy system.

Solar-assisted drying equipment combined with a heat pump and heat storage has been developed for drying peanuts [113,114].

A hybrid solar assisted heat pump dryer with photovoltaic modules proposed by Bhattacharya et al. [115]. This system was designed for drying process of vegetables and fruits for drying for fruits and vegetables.

Best et al. [116] designed and operated a solar assisted heat pump drying prototype system. The prototype had a drying chamber 3.78 m. Long divided in six sections, two of them with four drying trays and the other four sections with three each for a total of 20 trays. The heat pump consisted of modified 7 kW packaged air conditioning system. The compressor and the condenser were mounted in the frontal part of the equipment and the evaporator at the end of the drying chamber. The solar collector was fixed on top and consisted of a horizontal single glazed flat plate collector with air flowing on both sides of the black painted absorber. The advantage of the low temperature and better control in the drier showed that the heat pump assisted solar drying system is an excellent alternative to traditional drying systems.

Hawlader et al. [117] designed and built a solar assisted heat pump dryer and water heater, as shown in Fig. 9. The experimental set-up comprised of two separate paths which used for air and refrigerant. Solar air collector, air-cooled condenser, auxiliary heater, blower, dryer unit, evaporator, and temperature and flow control devices were in the air path. The refrigerant path consists of a vapour-compression heat-pump unit, with collector evaporator, an open-type reciprocating compressor, evaporator pressure regulators, expansion valves, condenser tank, and a fan-coil unit. The two evaporators are connected in parallel with individual expansion valves. Evaporator 1 acts as a dehumidifier and Evaporator 2 performs as an evaporator collector. A bare flat-plate solar collector was used as the evaporator and R134a as the refrigerant. The values of COP, obtained from the simulation and experiment are 7.0, and 5.0, respectively, whereas the solar fraction (SF) values of 0.65 and 0.61 are obtained from simulation and experiment, respectively.

In another study Hawlader and Jahangeer [118], presented the performance of the solar assisted heat pump dryer and water heater investigated a COP value of 7.5 for a compressor speed of 1800 rpm was observed. In the drying of green beans, a specific moisture extraction rate value of 0.65 for a material load of 20 kg and compressor speed of 1200 rpm was obtained.

In north china, agriculture products may be harvested above safe storage moistures to prevent excessive field losses. A solar-assisted heat pump drying system (SAHP) with an energy storage tank has been proposed to meet the demand in this field. The drying system is designed in such a way that some of the components can be isolated depending on the weather conditions and usage pattern. The performance of the whole system has been modelled and investigated under a typical summer day of the city Baoding, China. Results show that the coefficient of performance (COP) of the SAHP drying system is 5.369, while it is 3.411 without solar energy inputs. With an energy storage tank, the SAHP drying system performs more stable and modulates the mismatch between solar radiation and the energy needed in the night. Other discussions on collector numbers, drying time and drying temperature are also processed, which will be helpful to apply the system in China [119].

Experiments were conducted on the solar assisted heat pump dryer by Hawlader et al. [120] to compare the performance of an evaporator–collector and an air collector used in an integrated solar system. It was found that the evaporator–collector performed better than the air collector in a solar assisted heat pump drying system. The air collector efficiency was raised because of higher mass flow rates of air and using of dehumidifier in system. The range of efficiency of the air collector, with and without dehumidifier, was found to be about 0.72–0.76 and 0.42–0.48, respectively. It was also revealed that the efficiency of the evaporator–collector was higher than that of the air collector and it increased with increment of refrigerant mass flow rate. A

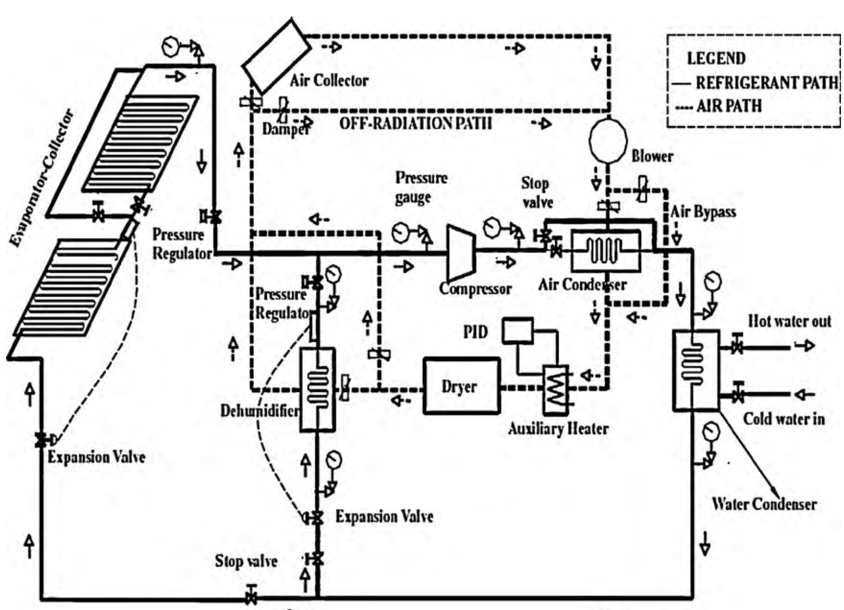


Fig. 9. Schematic diagram of the solar assisted heat pump dryer and water heater [117,118,120].

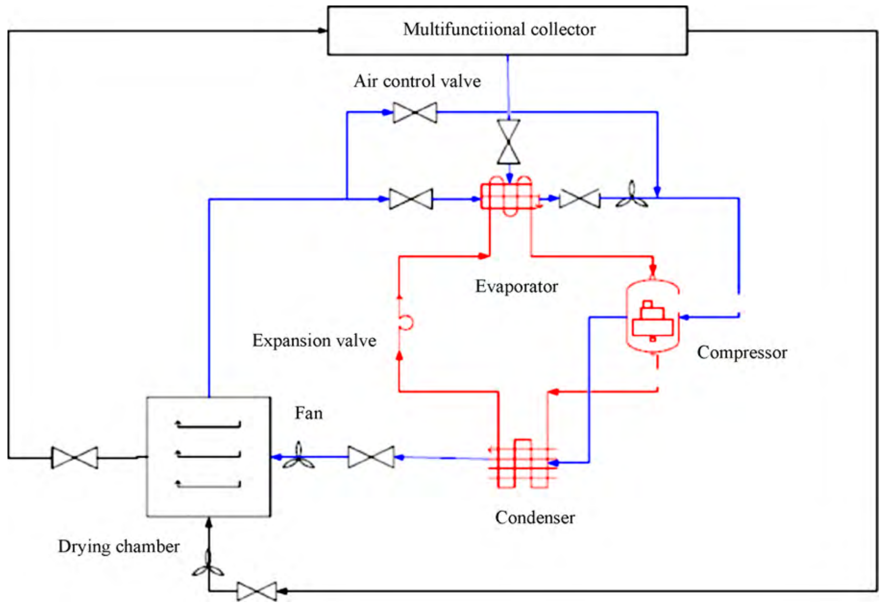


Fig. 10. Solar assisted heat pump drying using multifunctional solar collector-schematic diagram [126–128].

maximum evaporator–collector efficiency of 0.87 against a maximum air collector efficiency of 0.76 was obtained.

5.1.1. Hybrid solar assisted heat pump dryer (SAHPD) system

In tropical countries like Malaysia which has high relative humidity of 70–90% thought the year [121–123], the problem of humidity, uncertainties of the weather and unpredictable solar radiation intensity is very high [124], therefore, a heat pump dryer using multifunctional solar thermal collector designed and studied at Universiti Kebangsaan Malaysia (UKM) with considering the above factors [125]. This system consists of five main components: vapour compression heat pump system, multifunctional solar thermal collector, drying chamber, air duct and solar collector hot air channel (Fig. 10). The multifunctional solar thermal collector attached to the system used to maintain the power in the drying chamber and also to increase the system efficiency and consists of aluminium rods and fins to transfer heat to and from the air passing through it. The collector is covered by the transparent plastic sheet on the top, and insulated by rubber foam on the bottom. The multifunctional collector is designed to operate as heat collector during sunshine hours and as evaporator during night hours or when solar radiation is insufficient. Therefore, it will increase the overall efficiency of the system and also extended the operation time [126–128].

Four set of experiments were carried out in the laboratory with and without the multifunctional solar thermal collector, the first experiment was conducted with the heat pump as the source of heat for drying purposes without the solar collector, in this case heat pump provides a slow drying process, but it was a good dehumidifier. It took 80 min to increase the air temperature in the drying chamber from 30 to 40 °C. During the period, the humidity decreased from 80% to 45% (Fig. 11) and after 180 min of operation, the humidity of the air in the evaporator decreased to 24% and the air temperature in the drying chamber increased to 47 °C. The experiment was performed with no drying load.

The second experiment was done with the multifunctional thermal collector attached to the system. Hence extra heat from solar energy was collected to supplement to drying activity. A solar simulator with 12 halogen lumps, with capacity of 150 W each, was used in the experiment. At constant solar radiation of 440 W/m^2, the air temperature in the drying chamber increased from 34 to 38 °C in 20 min. If the system used heat pump only, it took 25 min to achieve the same temperature. Combining the two source of heat will make the drying more efficient, and at the same time, reduces the power used for the heat pump (Fig. 12).

The third experiment was conducted when the thermal collector acted as a cooling system, to cool the air before it entered the evaporator. During operation, the multifunctional thermal solar collector was closed not to allow outside air to enter the system, and the solar simulator was shut off. The system worked without additional heat from solar radiation, therefore only the heat pump maintains the air temperature in the drying

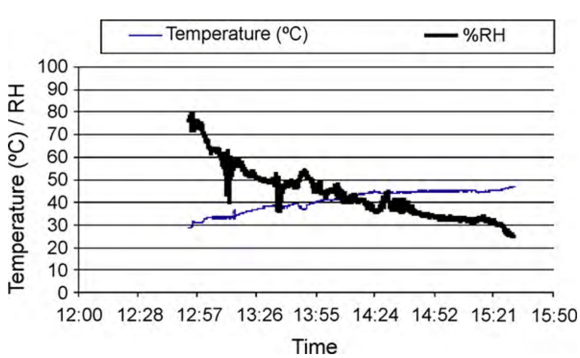


Fig. 11. Heat pump drying capacity: reducing air humidity from 80% to 45%, and increasing air temperature from 30 to 40 °C in 20 min.

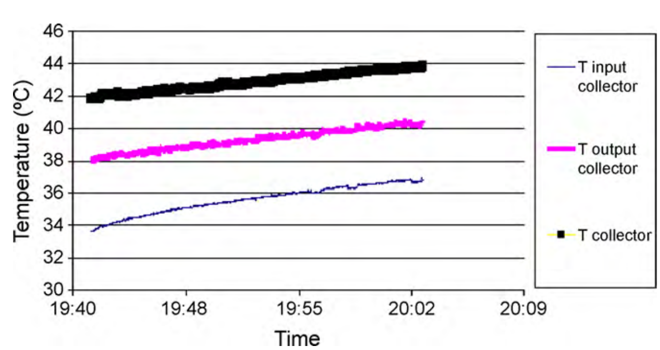


Fig. 12. The variation of air temperature in the drying chamber using multifunctional solar collector at solar radiation of 440 W/m^2.

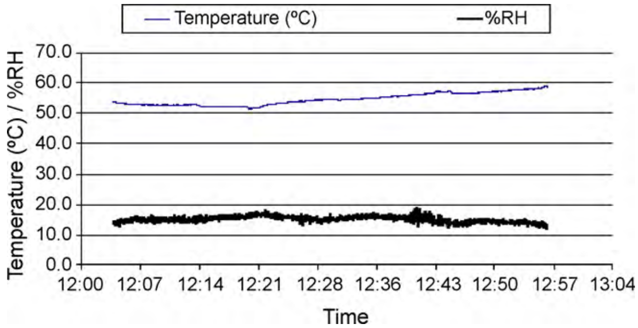


Fig. 13. Temperature and relative humidity of the air in the drying when the solar collector acts as a cooler.

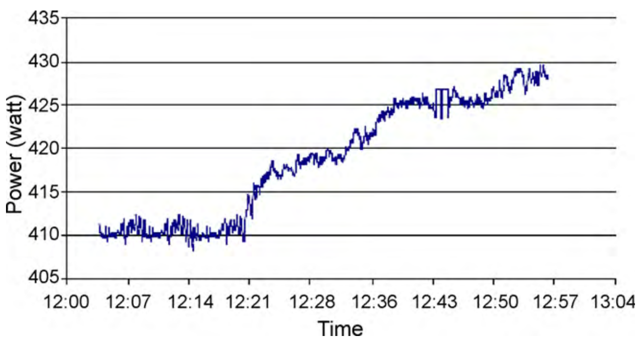


Fig. 14. The multifunctional solar thermal collector as a cooler. Note that the power for the compressor starts to increase after 15 min of operation.

chamber. The air temperature in the drying chamber was 55 °C and humidity was 15% and the humidity in the multifunctional solar thermal collector was found to be 20%. This means that the collector removed the heat from the drying chamber and brought it to evaporating chamber for evaporation process (Figs. 13 and 14).

Finally, the fourth experiment was operated where the thermal collector acted as an evaporator to evaporate drying air before it entered the drying chamber; the experiment was carried out at low temperature environment. During drying process, the environment temperature was set at 5–20 °C. The cooler air outside the drying chamber would cool the aluminium rods and fins; as such water in hot air with high humidity in the drying chamber would condensate. In other words the thermal collector acted as evaporator to remove part of water in humid and hot air in the drying chamber (Fig. 15).

The preliminary results of experimental work revealed that this system is environment friendly and can be used anywhere in four season countries. The system is ready for drying of high quality

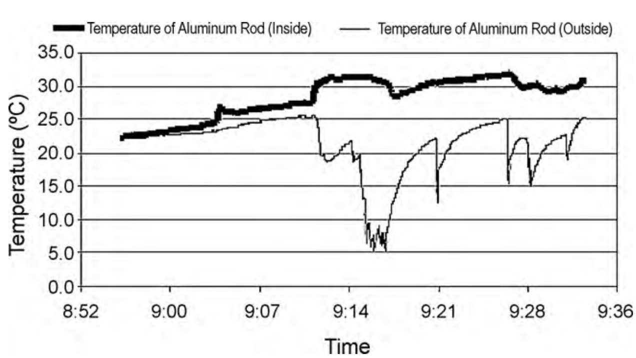


Fig. 15. Multifunctional solar thermal collector acted as evaporator (to condensate water in the drying chamber).

products. Further experiments are being conducted on the system to study its performance under various conditions.

5.1.2. Solar assisted drying chemical heat pump system

Integration of solar thermal system to the chemical heat pumps (CHPs) would assist in expanding the utilization of CHPs and also for many applications in the tropical regions [72].

Employment of solar energy in chemical heat pumps have been reported where heat was stored in chemical substances in CHP and it was concluded that in this system heat did not have losses due to temperature differences [129], and low temperature-source such as solar thermal energy could be upgraded to satisfy to satisfy the requirements at higher level by exothermic reaction. Solar collector directly integrated to a U-shape tubular chemical reactor as receiver/reactor was developed for reforming of methane [130].

A design of an ammonia based thermochemical solar energy storage and transport system has been developed using directly irradiated catalyst filed tubes (receiver/reactor). Experimental study showed that simple tube and tube counter flow heat exchanger are adequate for obtaining higher storage efficiencies [131].

A solar adsorption heat pump utilizing the zeolite–water pair using continues coating of the zeolite on stainless steel wire gauzes has been developed. They were placed vertically in the collector. The solar collector consisted of two separate reigns. T he variation of solar COP to the thermal gradient of (0–30 °C) was between 0.06 and 0.13 [132].

Amongst applications of solar assisted chemical heat pumps, dryer systems had not been reported heretofore, but recently a solar assisted chemical heat pump dryer (SACHPD) has been designed, fabricated and tested in Malaysia. The schematic diagram of system is shown in Fig. 16 [133]. The system consists of four mean components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber. In this study, a cylindrical tank is selected as a storage tank. The chemical heat pump unit contains of reactor, evaporator and condenser. In the chemical heat pump a solid gas reactor coupled with a condenser or an evaporator. The reactor contains a salt which reacts with the gas, the reactions used in this study is:

$$CaCl_2{\cdot}2NH_3 + 6NH_3 \rightarrow CaCl_2{\cdot}8NH_3 + 6\Delta Hr$$

The drying chamber contains multiple trays to hold the drying material and expose it to the air flow.

The general working of chemical heat pump occurs in two stages: adsorption and desorption. The adsorption stage is the cold production stage, and this is followed by the regeneration stage, where decomposition takes place. During the production phase, the liquid–gas transformation of ammonia produces cold at low temperature in the evaporator. At the same time, chemical reaction between the gaseous ammonia and solid would release heat of reaction at higher temperature. The incoming air is heated by condensing refrigerant (ammonia) and enters the dryer inlet at the drying condition and performs drying. After the drying process, part of the moist air stream leaving the drying chamber is diverted through the evaporator, where it is cooled, and dehumidification takes place as heat is given up to the refrigerant (ammonia). The air is then passing through the condenser where it is reheated by the condensing refrigerant and then to the drying chamber. The material dried is lemon grass.

A series of experiments have been performed under varied conditions for 2 days to evaluate the performance of a solar-assisted chemical heat pump dryer under the meteorological conditions of Malaysia. Two representative days for clear and cloudy conditions were presented. The hourly average values of solar radiation for typical clear and cloudy days in December for

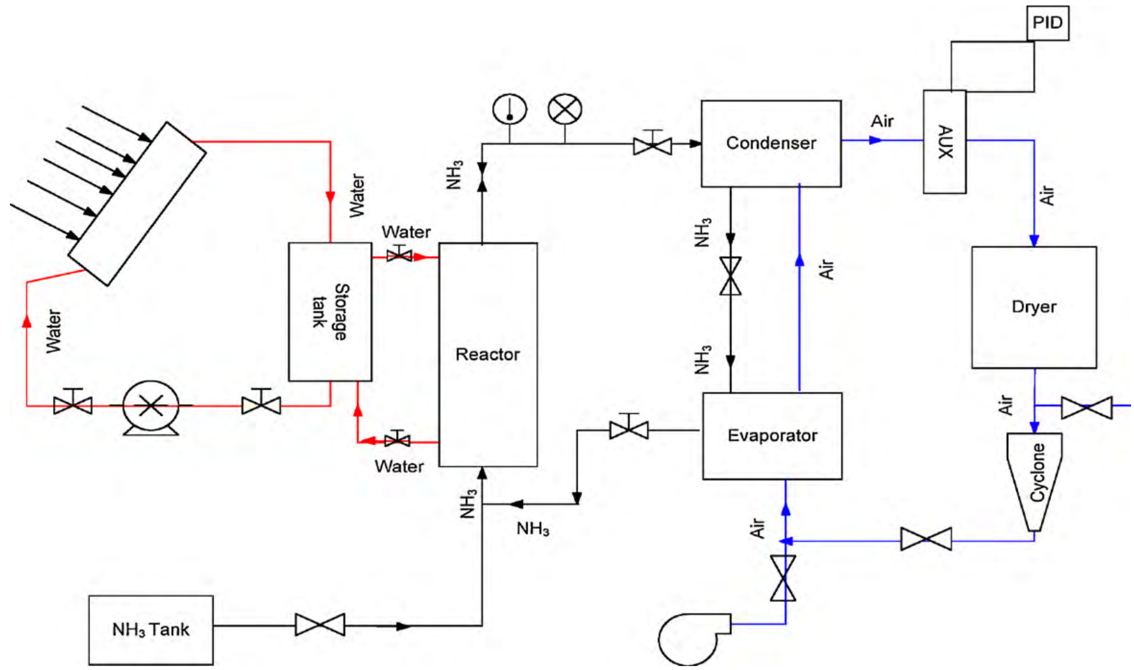


Fig. 16. Schematic diagram of solar assisted chemical heat pump dryer [133].

Malaysia showed (Fig. 17), while the average values of ambient temperature for the same days showed in Fig. 18.

The maximum values of solar fraction from the experiments on clear and cloudy days were 0.713 and 0.322 (Fig. 19), respectively; whereas the coefficient of performance of CHP (COP^h) maximum values of 2 and 1.42 (Fig. 20) were obtained from the experiments on clear and cloudy days, respectively [134–136].

The total system energy output from the experiment on a clear day was 51 kWh against 25 kWh on a cloudy day (Fig. 21). Any reduction of energy at the condenser as a result of decrease in solar radiation will decrease the coefficient of performance as well as the efficiency of drying [135].

The results showed that any reduction of energy at the condenser as a result of a decrease in solar radiation will decrease

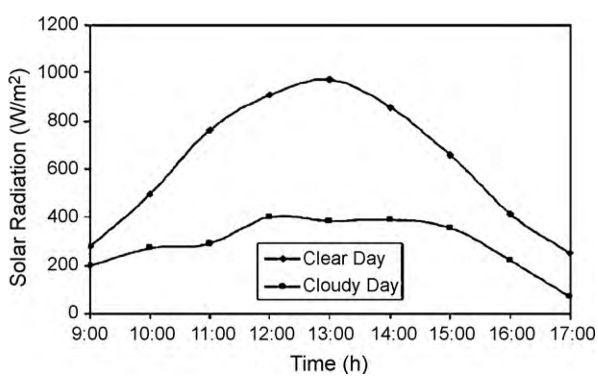


Fig. 17. Average hourly radiation in Malaysia in December.

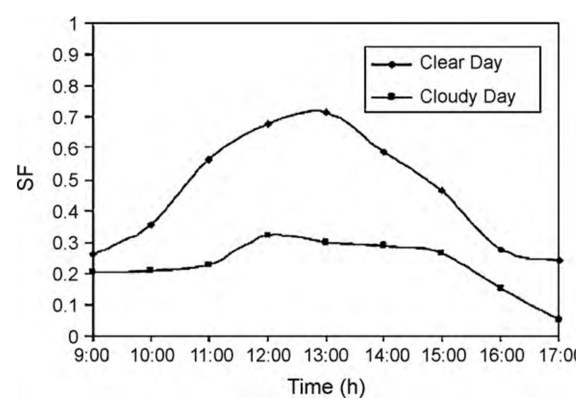


Fig. 19. System solar fraction.

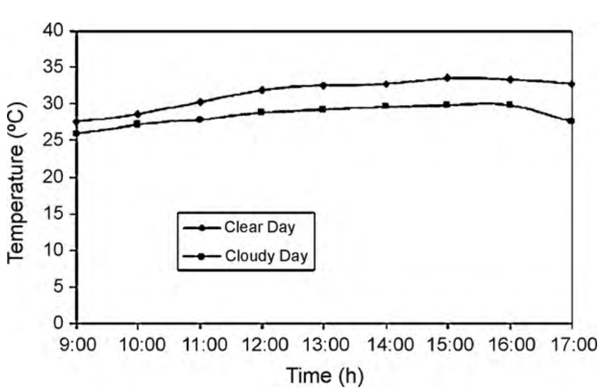


Fig. 18. Average ambient temperature in Malaysia in December.

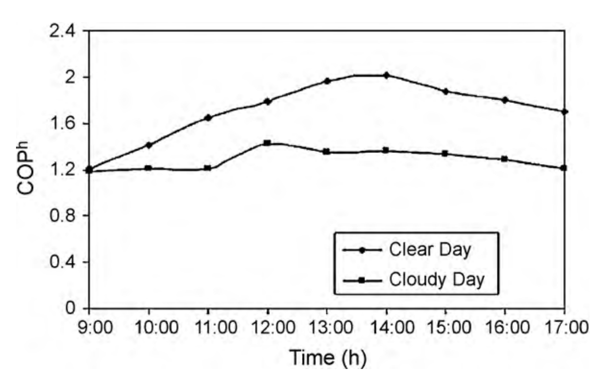


Fig. 20. Coefficient of performance of SACHPD.

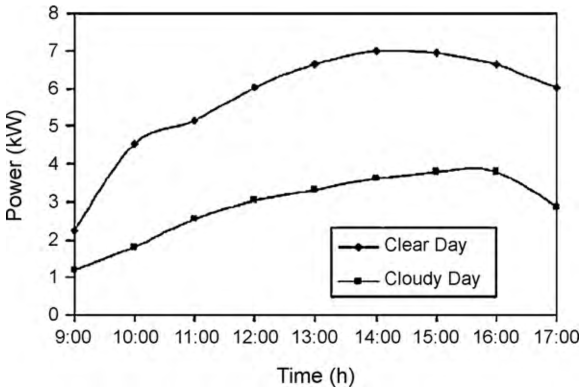


Fig. 21. System power output.

the coefficient of performance as well as the efficiency of drying [135,136].

6. Future trends in SAHPD research and development

Utilizing free and renewable solar as well ground resource of energy are the way forward in SAHPD research and development. It has several advantages including low carbon and compatibility of storing thermal energy and ability to utilize waste heat by extracting heat from them and then compressing it to raise the temperature significantly, efficient thermal energy use for drying applications can be obtained using air source, chemical and ground source heat pumps which they are environment friendly systems.

Looking into the future direction of SAHPD technologies, it is possible to consider new demands on better energy efficiency, lower environmental impact, and utilization of renewable energy for drying and better quality products at lower total cost. Currently, the major driving force for innovation in drying techniques is the need to produce better quality products at higher throughputs. This goal can be reached in several possible ways such as using multiple stages air source solar assisted heat pump dryer that can produce a high quality dried product at a lower cost is of these methods.

The most important component in SAHPD is the solar collector. Both air and water based collectors can be used. Innovation in the design of solar collector is very important. Collector performance should be increased in order to accept for commercial application. Many studies have been conducted on enhancement of the thermal performance of solar collectors, but the performance of the different types of solar and PV/T water based collectors, glass covered, selective surface of solar assisted heat pump systems have not been investigated. A lot of research works should be carried out in this area for investigating the effects of using solar collector water based, PV/T water based on improving Coefficient of Performance (COP) of dryers.

The ground source or geothermal heat-pump system is supposed to be energy efficient means of heating next to solar. Therefore, merging both technologies in domestic and industrial applications in order to obtain heat particularly for drying applications would be easily implemented for sustainable energy development, increasing of energy efficiency and lessen environmental pollution.

Most solar energy processes require an auxiliary (i.e., conventional) energy source. Hence, solar assisted system includes both solar and conventional equipment and the annual loads are met by a combination of the sources. In essence, solar energy equipment is bought today to reduce tomorrow's fuel bill [137]. From the individual techno-economics analysis of the solar drying systems and heat pump dryer, it can be concluded that due to more latent heat for recovery, improved product quality, energy efficiency and yield of the dried products and more operating hours, the economic payback period of SAHPD systems are considerably decreased. Thus, much more attention should be paid to economical study of SAHPD systems in order to prove economics of these systems.

7. Conclusions

In this study a review of the some available literature on SAHPD systems with the view of enabling an easier comparison of the findings obtained by various researchers has been conducted. However, a lot of research work still needs to be done for large-scale applications in industry and for the replacement of conventional dryers and heat pump dryers. The results of studies of SAHPD systems indicated that the COP of these systems can be much better than that of conventional heat pump dryers and also quality of products has been improved. SAHPD systems with respect to product quality control, reduced energy consumption and reduced environmental impact can be very useful. For heat sensitive materials improved quality control can be achieved due to low drying temperatures and independency of the outdoor air. Solar assisted heat pump dryers offer one of the most lucrative possibilities for future environment friendly drying systems. These systems are potentially more efficient than the conventional dryers. In addition, in these systems reduced energy consumption is achieved due to the high coefficient of performance of the solar assisted heat pump dryer and the high thermal efficiency of the dryer when properly designed.

Very few studies are available regarding economical studies, performance, exergy and energy analysis and utilization of different types of collectors of SAHPD systems. Therefore, further attempts should be conducted in this field and the integration of combined renewable energy technologies into the heat pump drying systems might be much more developed.

Solar assisted chemical heat pump drying systems can also offer practical ways for effective energy utilization and introduce environment friendly drying systems due to take advantages of waste heat. These systems are sustainable and environment friendly since it utilized of free solar energy and provided promising application for drying in the future.

As ground source heat pump systems utilize energy less than that it produce, employ free energy from ground and have low operating cost, it will be more energy efficient if solar energy incorporate as another free and renewable energy source for domestic and industrial applications, especially for drying systems.

Acknowledgements

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